IMPLEMENTATION OF A NOVEL STRUCTURAL HEALTH MANAGEMENT SYSTEM FOR STEEL BRIDGES

Robert Mason, Michael Miller, and Lawrence Gintert
Concurrent Technologies Corporation (*CTC*)

Vincent Hock, Richard Lampo, and Steven Sweeney
U.S. Army Corps of Engineers, Engineer Research and Development Center,
Construction Engineering Research Laboratory (ERDC-CERL)

Keith Chandler
Chandler Monitoring Systems, Inc.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **FEB 2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Implementation of a Novel Strucural Health Management System for Steel Bridges**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Corps of Engineers,Engineer Research and Development Center,Construction Engineering Research Laboratory (ERDC-CERL),Champaign,IL,61822**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
2010 U.S. Army Corrosion Summit, Huntsville, AL, 9-11 Feb

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**35**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Overview

- Problem Description
- Objectives
- Technical Approach
  - Team
- Structural Evaluation
- System Design
  - Sensor Systems Employed
  - Logic
- System Installation on Government Bridge
- Data Acquisition and Analysis
- Next Steps
- Summary

Problem Description

- Corrosion of steel bridges remains a critical infrastructure concern
  - Corrosion of U.S. highway bridges costs economy $8.3M annually *(Source: Federal Highway Administration (FHWA))*
  - 25% of U.S. bridges are structurally deficient or functionally obsolete *(Source: FHWA)*
  - 503 U.S. bridges failed over an 11 year period (100 due to corrosion) *(Source: ERDC-CERL)*

Problem Description (cont.)

- Current method of monitoring – routine inspection – has limitations
  - Several techniques employed - visual, dye penetrate, ultrasonic, and radiographic non-destructive testing methods
  - May not detect hidden cracks in built-up structures
  - Unable to determine if defect is actively growing

Objectives

- Demonstrate and validate state-of-the-art and emerging innovative technology approaches for remote structural health and corrosion degradation monitoring of steel bridges
- Integrate technologies into a novel Bridge Structural Health Monitoring (SHM) System in which all components work cooperatively to greatly reduce risk of catastrophic failure by providing advance warning of growing structural problems caused by corrosion/materials degradation
- Employ system on two subject bridges

Objectives (cont.)

- Subject Bridge 1 – Government Bridge, Rock Island, IL
  - Steel truss through deck
  - One of oldest in inventory – opened in 1896
  - About 10,300 vehicles per day (lower deck)
  - About five trains
    per day (upper deck)

Objectives (cont.)

- Subject Bridge 2 – I-20 Bridge, Vicksburg, MS
  - Steel truss through deck
  - Opened in 1973
  - About 23,000 vehicles per day
  - Westward movement of bridge piers E-1 and E-2 on east side

Technical Approach

- Conduct structural assessment of subject bridges to determine optimal types and locations of sensors
- Integrate optical and other sensors into a novel SHM system specifically tailored to the subject bridges
- Design software that can not only collect data but can also interpret to provide early warning of areas of concern
- Implement system on Government Bridge in first year’s effort

Technical Approach (cont.)

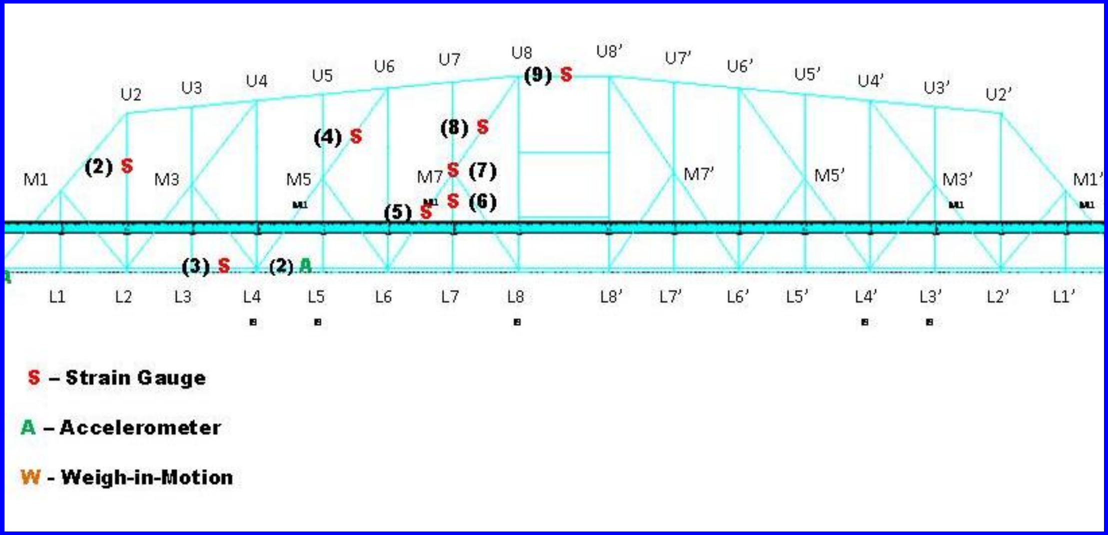
- For the Government Bridge – design and implement SHM system utilizing:
  - Corrosion sensors – two types plus corrosion coupons
  - Fiber Bragg Grating (FBG) Accelerometers – modal response, monitor abnormal vibration characteristics
  - FBG Strain gauges – monitor abnormal deflections
  - Acoustic Emission (AE) sensors – monitor crack growth

Team Members

- U.S. Army Corps of Engineers, Engineer Research and Development Center Construction Engineering Research Laboratory (ERDC-CERL)
- Mandaree Enterprise Corporation (MEC)
- Concurrent Technologies Corporation (*CTC*)
- O'Donnell Consulting Engineers, Inc.
- Chandler Monitoring Systems, Inc.
  - Carlyle Consultants
  - Defense Science and Technology Office (DSTO), Australia
  - Cooperative Research Centre for Integrated Engineering Asset Management (CIEAM), Australia
- Input from Office of the Secretary of Defense (OSD), other ERDC personnel, relevant Departments of Transportation (DOTs) and Directorates of Public Works (DPWs)

Structural Evaluation

- Evaluate existing structural characteristics of both bridges using 3D Finite Element models
  - Establish current structural health
  - Determine critical failure points
  - Establish ideal areas for sensor placement



System Design – Sensor Systems Employed

- Corrosion Sensors – two types
  - Commercial off-the-shelf (COTS) electrical resistance (ER) sensors
  - Experimental ER sensors (provided by CIEAM)
- Test coupon racks

COTS ER Probes

CIEAM ER Sensor

Corrosion Coupon Rack

System Design – Sensor Systems Employed (cont.)

- Optical Sensors – Fiber Bragg Gratings (FBGs)
  - Fiber cores with photo-imprinted FBGs to change refractive index
  - Laser input signals sent through fiber core reflect off FBGs
  - Each FBG sensor has different wave length and spectural operating window band
  - As pressure or temperature changes, reflected wave length changes, providing data
  - Accelerometers and strain gages, as well as temperature compensation

System Design – Sensor Systems Employed (cont.)

- **FBG technology allows monitoring *many* sensors (>100 in some cases) on *one fiber***
  - Each sensor on fiber is wavelength-specific, providing implicit identification and ability to *multiplex* data.
  - Simplifies cabling and instrumentation

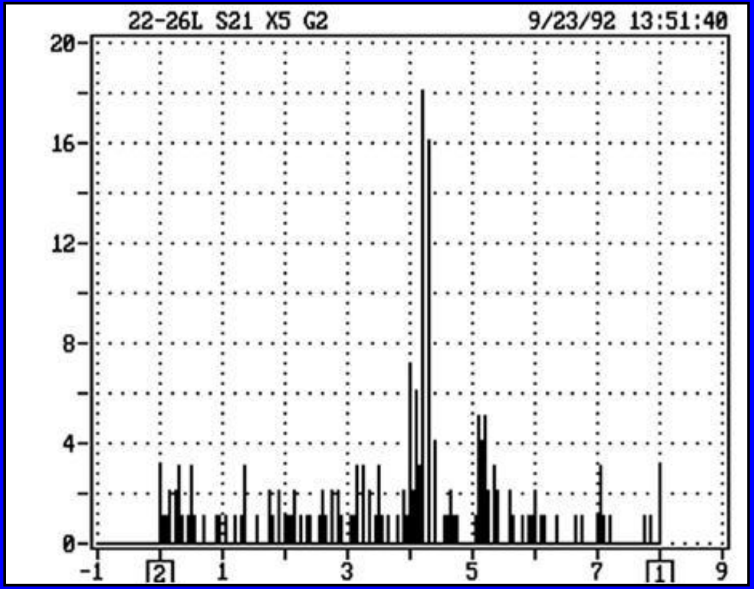
Cabling and instrumentation for 400 *wired* strain sensors

Cabling and instrumentation for ≥ 640 multiplexed *fiber-optic* strain sensors, inside environmental enclosure with heat exchanger

System Design – Sensor Systems Employed (cont.)

- AE Sensors
  - Detect and locate active, growing defects
  - Totally inspect monitored area for all defects, covering beams, gussets, stringers, and all hidden structural members
  - Only normal bridge traffic and/or wind loads needed
  - Work on both steel and composite bridges
  - Locate cracks by actual growth
  - Computerized
  - Quick - results available in real-time during testing

System Design – Sensor Systems Employed (cont.)



- AE sensors on I-80 Bryte Bend bridge
  - Box-beam bridge design
  - Inappropriate material selection resulted in cracks
  - AE detected 1/16" long fatigue crack, hidden under paint but growing under traffic loading

System Design - Logic

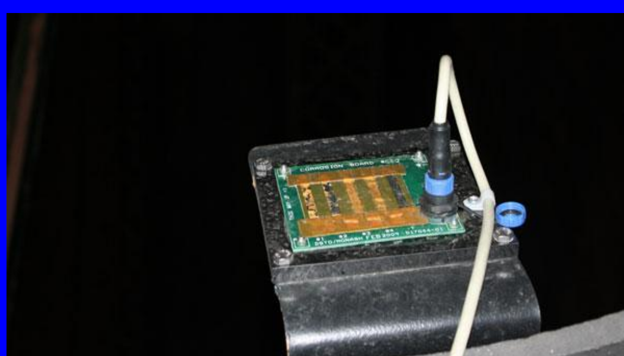
- Logic flow established

Bridge Structural Health Monitoring System Scenarios and Sensors Matrix									
Scenarios	Corrosion Sensors	FBD Strain Sensors	FBG Temperature Sensors	Deflection/ Displacement Sensors	Acoustic Emissions Sensors	Tilt Meters	Camera system	Water Level Gage	Accelerometers
Accident on bridge with damage to truss	No	Maybe	Maybe	Maybe	Maybe	Maybe	Yes	No	Yes
Bridge overload - high strain	Maybe	Yes	No	Yes	Maybe	Maybe	Yes	Maybe	No
Creep of Bridge Structure	Maybe	Yes (A)	No	Yes (A)	No	Maybe	Yes	No	No
Excess deflection	Maybe	Yes	Maybe	Yes	Maybe	Maybe	Yes	Maybe	Yes
Extreme corrosion - reduced cross section	Yes	Maybe	No	Maybe	No	Maybe	Yes	No	No
Extreme temperature due to fire on bridge	No	Maybe	Yes	Maybe	No	No	Yes	No	No
High water condition	No	No	No	No	No	No	No	Yes	No
Lightning	Maybe	No	No	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe
Loss of any individual signal	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe
Natural Frequency Shift of Bridge Structure	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Yes	Maybe	No
Pier Rotation	No	Maybe	No	Maybe	Maybe	Yes	Yes	Maybe	Yes
Seismic Activity	No	Maybe	No	Maybe	Maybe	Yes	No	Maybe	Yes
Structural crack growth	Maybe	Maybe	No	Maybe	Yes	Maybe	Yes	Maybe	No
Train accident/derailed	No	Maybe	No	Maybe	Maybe	Maybe	Yes	No	Yes
Total System Failure	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

System Installation on Government Bridge

Installing fiber on lower portions of bridge

Preparing bridge strut for tack welding



CIEAM corrosion sensor installed

AE sensor installed

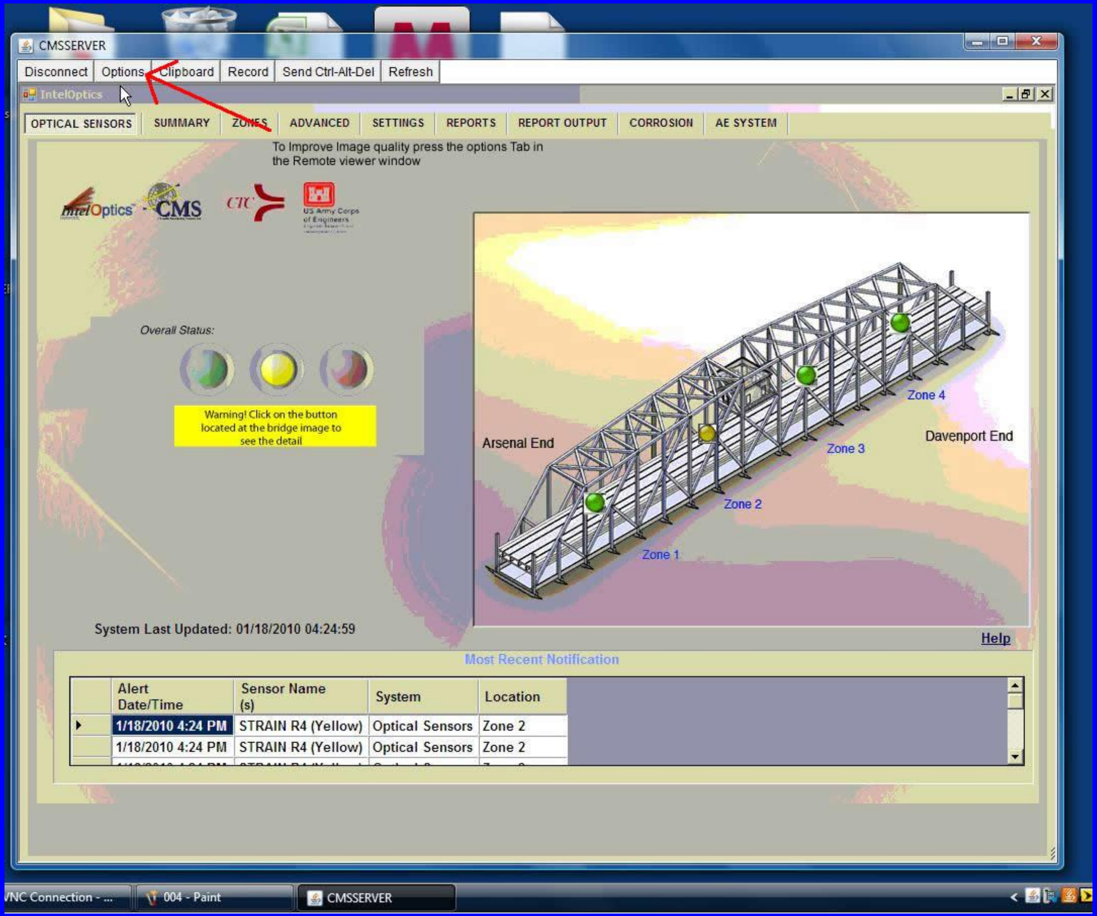
Data Acquisition and Analysis

- Graphical user interface (GUI) accessible via web

Data Acquisition and Analysis (cont.)

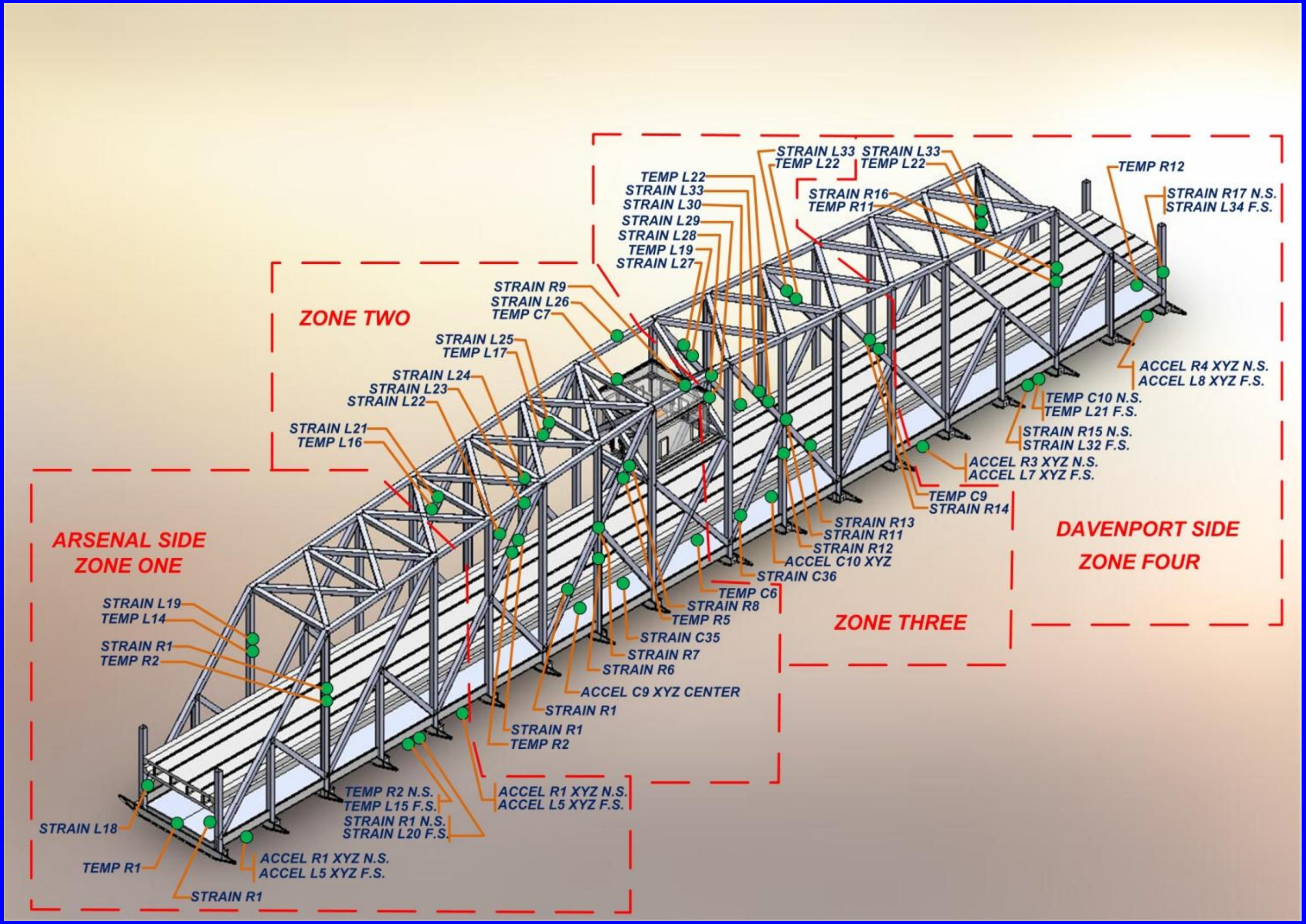
- Summary Page
  - Graphical depiction of bridge
  - Four quadrants of sensors
  - Separate screens for corrosion, optical, AE sensors

Data Acquisition and Analysis (cont.)



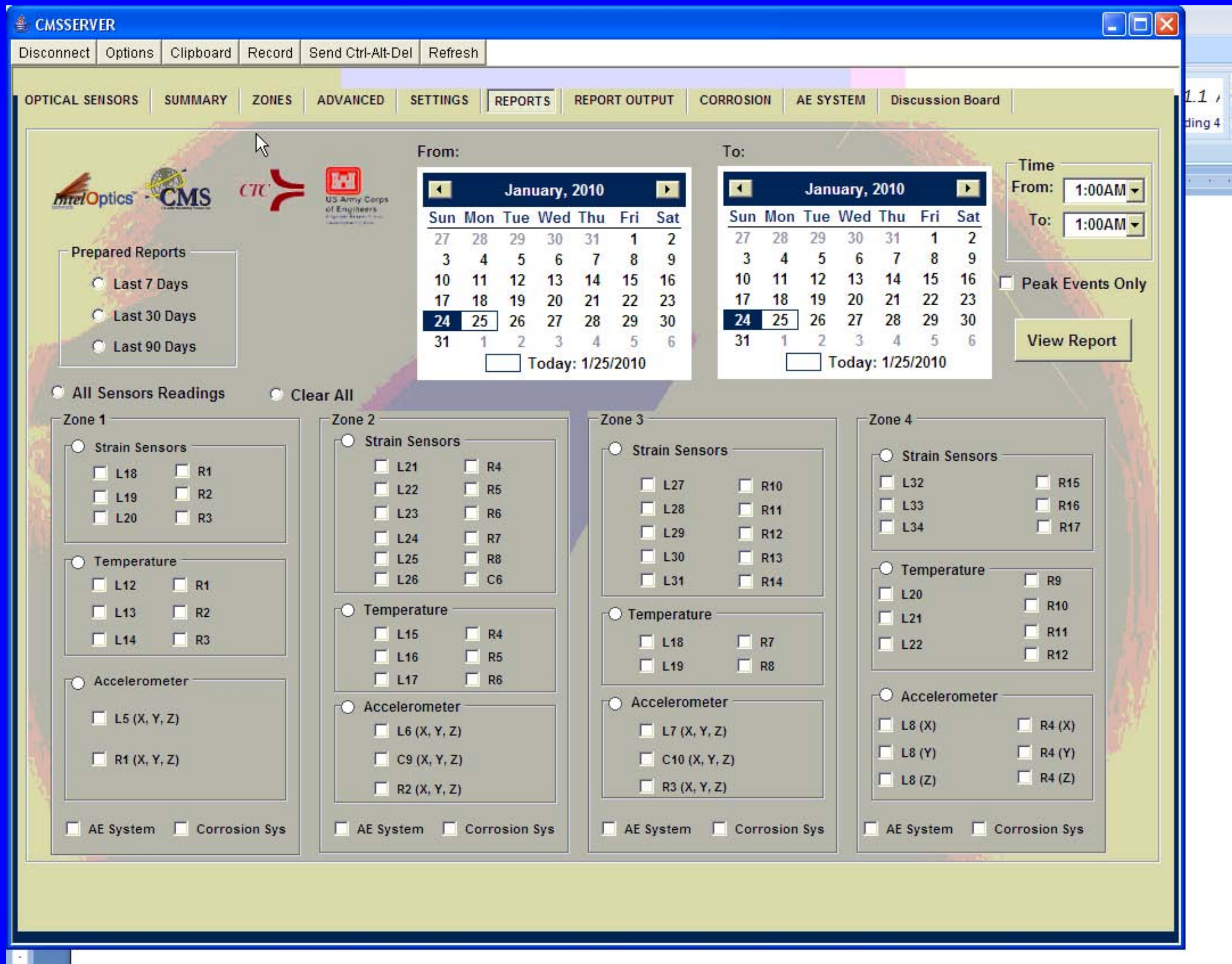
- Optical Sensors Page
  - Graphical depiction of bridge, four quadrants
  - Green-yellow-red to show overall status of quadrant

Data Acquisition and Analysis (cont.)



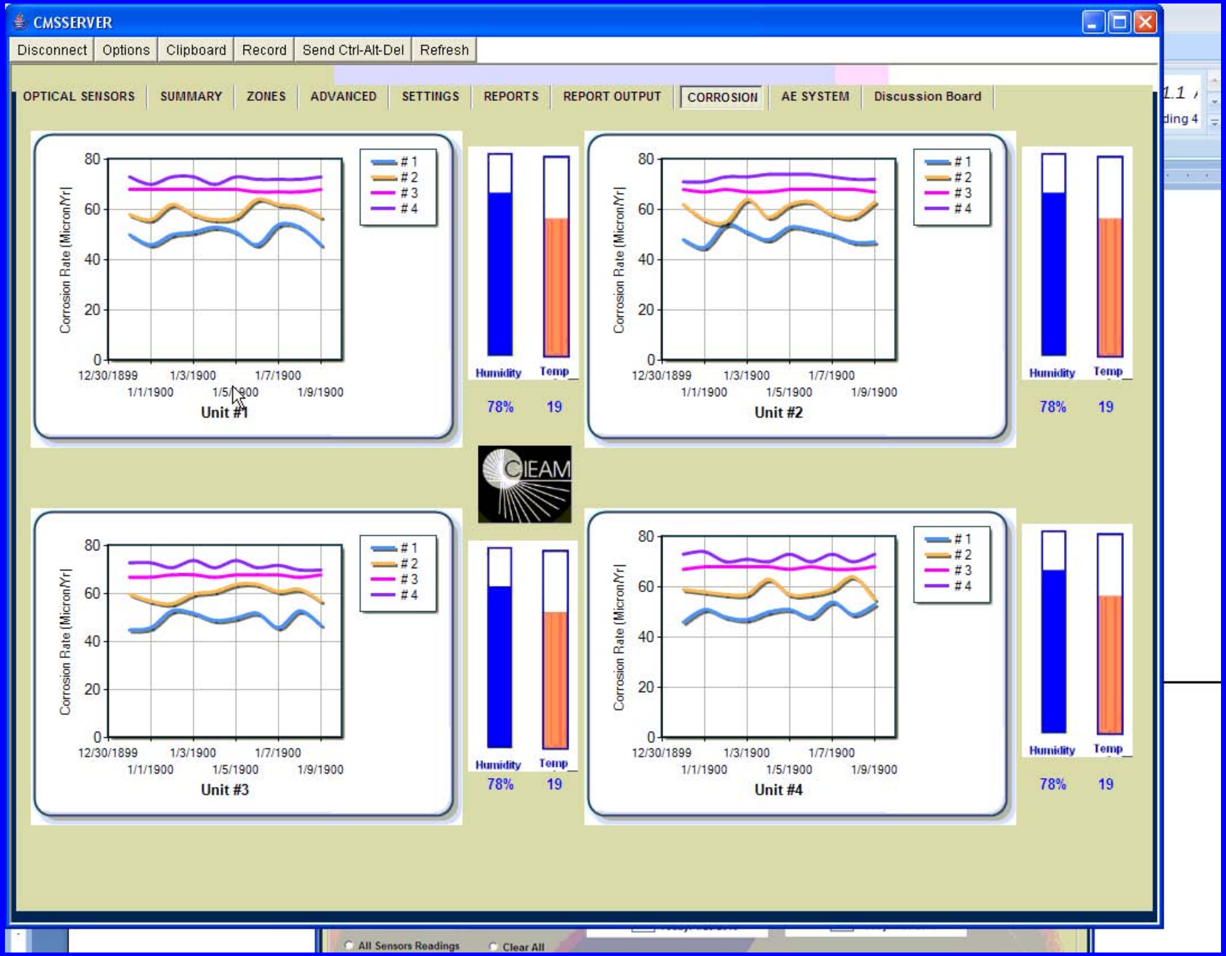
- Optical Sensors Page
  - Graphical depiction of bridge, four quadrants
  - Green-yellow-red to show status of all optical sensors in all zones

Data Acquisition and Analysis (cont.)



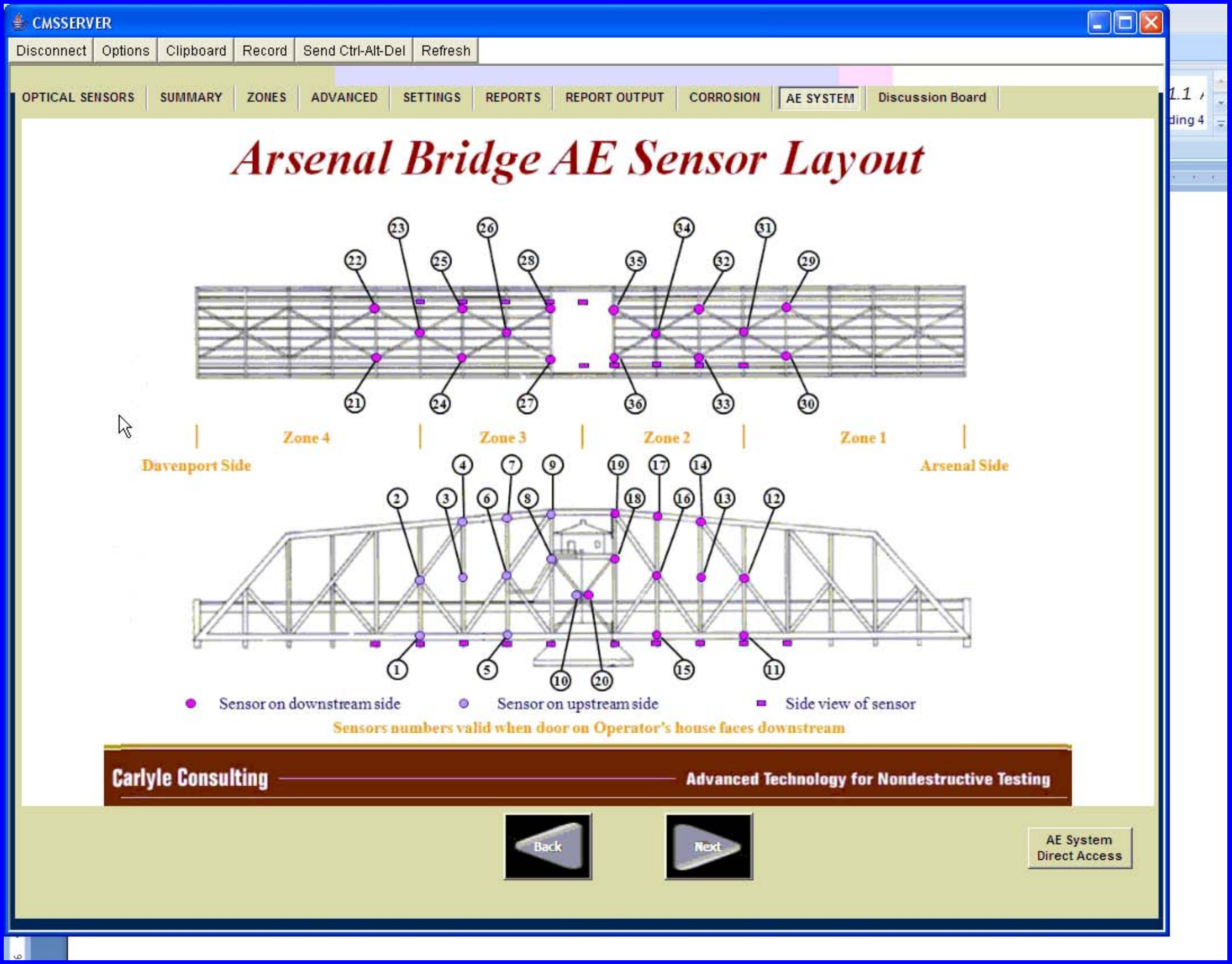
- Reports Page
  - Allows generation of reports by zone, specific sensor(s), and/or date

Data Acquisition and Analysis (cont.)



- Corrosion Sensors Page
  - Also readouts for humidity and temperature

Data Acquisition and Analysis (cont.)



- AE Sensors Page
  - Finalizing readout appearance

Next Steps

- Monitor Government Bridge SHM system for one full year
- Install similar system on the I-20 bridge
  - Corrosion sensors – two types plus corrosion coupons
  - Accelerometers – modal response, monitor abnormal vibration characteristics
  - Strain gauges – monitor abnormal deflections
  - Tilt sensors
  - Deflection/displacement gauges – monitor movement of piers and associated stress to structural members

Summary

- The corrosion of steel bridges continues to be a critical infrastructure concern
- A novel sensor system, based on optical FBG sensors but incorporating other unique types of sensors and technologies, has been designed and implemented on the Government Bridge
- The system will provide 24-hour, thorough evaluations of bridge structures, including instantaneous warnings of potential failure spots (visible or not)

Acknowledgments

- This work was funded by ERDC-CERL through the OSD as part of the Department of Defense Corrosion Prevention and Control Program.
- The authors wish to recognize the sponsors of this effort:
  - Office of Under Secretary of Defense, Office of Corrosion Policy and Oversight (Director, Mr. Dan Dunmire)
  - Deputy Assistant Secretary of the Army Acquisition Policy and Logistics (Army Corrosion Control Prevention Executive, Mr. Wimpy D. Pybus)
  - Assistant Chief of Staff for Installation Management (Mr. David Purcell)
  - Headquarters, U.S. Army Installation Management Command (Mr. Paul Volkman)

Acknowledgments (cont)

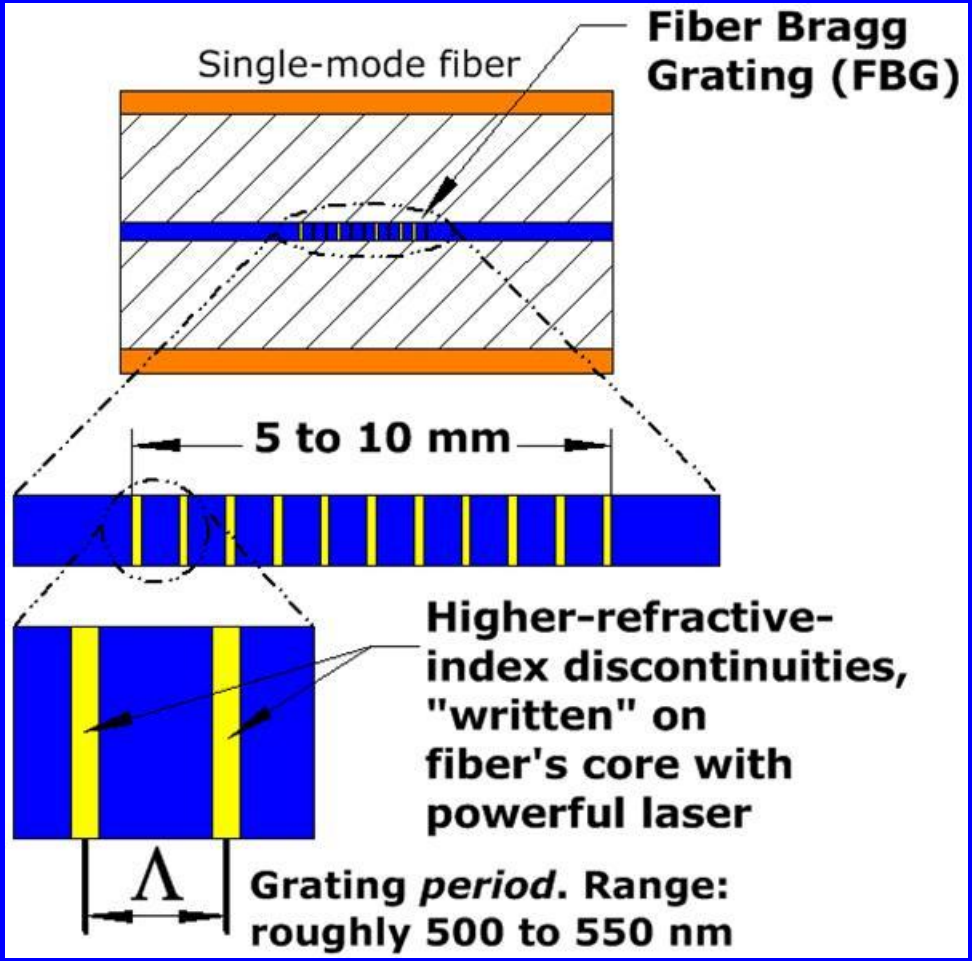
- The authors would also like to recognize key team members:
  - Mr. Richard Kinzie, OSD
  - Mr. Vincent Chiarito and Dr. Paul Mlakar, U.S. Army ERDC
  - Mr. Larry Cranford and Dr. Doug Neale, Mandaree Enterprises Corporation
  - Dr. William O'Donnell, Mr. Tony Hedderman, Mr. Don Shaw, and Mr. Jeremy Himes, O'Donnell Consulting Engineers Inc.
  - Dr. John Carlyle, Carlyle Consulting
  - Dr. Scott Wade, Monash University
  - Mr. R. Kirk Gallien P.E., P.T.O.E., Louisiana DOT
  - Mr. Mitchell K. Carr, Mississippi DOT
  - Mr. Christian Hawkinson, P.E., Rock Island Arsenal DPW

Thank You!

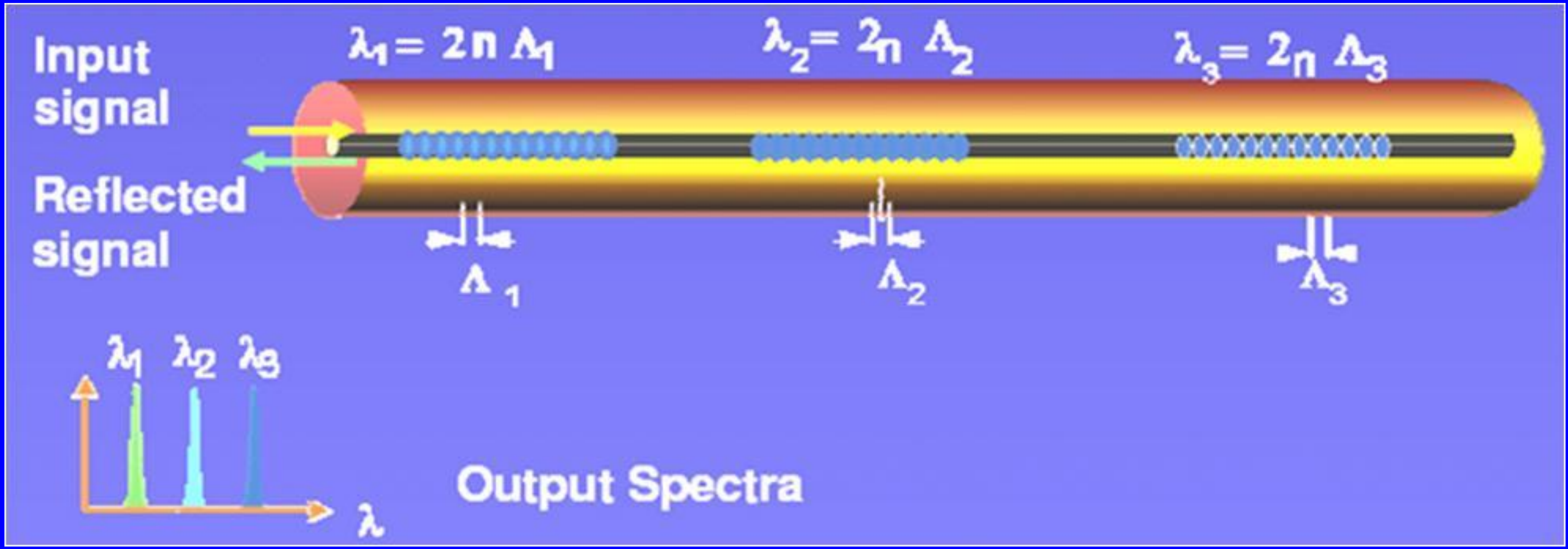
Questions?

BACKUP SLIDES

System Design - Fiber Bragg Gratings



Fiber Bragg Gratings (cont.)



- Typically can monitor up to +/-2500 microstrain ($\mu\varepsilon$)/FBG with up to 40 FBGs written-on or spliced-to each fiber, each FBG having a unique $\lambda_{\mathbf{Bragg}}$
  - Interrogator scans for and finds each unique-$\lambda_{\mathbf{Bragg}}$ peak
  - Software analyzes each unique-$\lambda_{\mathbf{Bragg}}$ peak and numerically logs its precise $\lambda_{\mathbf{Bragg}}$ value
- Can spread FBG locations over long distances of fiber
- Greatly simplifies cabling, instrumentation, and installation

Fiber Bragg Gratings (cont.)

- Benefits of FBG optical sensors
  - Established, proven technology
  - Fast, accurate, field-reliable
  - Resistant to fatigue and drift
  - Immune to electromagnetic interference
  - Resistant to corrosion, chemicals, water, and lightning
  - Large temperature range (-40 to +150˚C)
  - Signals can travel long distances (kilometers)
  - Small, light weight, easy to install
  - Surface mountable or embeddable into structures

System Design – Complete System